Effectiveness of Pre-Fire Fuel Treatments

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Executive Summary

This project investigated the severity of five recent wildfires that burned into existing fuel treatment areas. Paired plots straddled fuel treatment boundaries on similar slope and aspect so as to isolate treatment effects from confounding influences. Treatments spanned a range of types and ages at each study site. Study areas included the 2002 Hayman fire on the Pike National Forest, the 2003 Aspen fire on the Coronado National Forest, the 2003 Davis fire on the Deschutes National Forest, the 2004 Power fire on the Eldorado National Forest, and the 2004 Fischer fire on the Wenatchee National Forest. The data collected from these wildfires adds substantially to the existing information on fuel treatment effectiveness. Few previous studies document the effects multiple fuel treatments varying in type and age that were burned over by individual wildfires. While we urge caution in applying inferences from this study to areas beyond the mixed conifer forests we sampled, our results point to five key findings:

Fuel treatment effectiveness depends on type of treatment.
Treatments that included reduction of surface fuels were generally effective, with or without prior treatment of canopy fuels. But thinning followed by slash treatment produced the most impressive results. Thin-only treatments were generally ineffective and in some cases produced greater fire severity than adjacent untreated areas.

Fuel treatment effectiveness depends on treatment age.
While thin-only treatments were generally not effective, the most recent treatments of this type did produce significant reductions in fire severity. These thinnings were less than one year old when affected by wildfire and the resultant slash was probably still green. Treatments that included reduction of surface fuels were effective for up to a decade, while older treatments were not found to have a significant effect on fire severity at any site, regardless of treatment type.

Fuel treatment effectiveness depends on weather severity.
It is generally presumed that fuel treatments must be overwhelmed at some threshold of weather extremity. However, we observed fire severity reductions in several fuel treated areas that were affected by wildfire under some of the most extreme weather conditions on record. Only treatments that reduced both canopy and surface fuels in combination showed a significant correlation to weather conditions and the effectiveness of these treatments actually increased with weather severity. But whether this relationship will hold under the increasingly extreme weather conditions predicted by climate change scenarios remains to be seen.

Fuel treatment effects may extend beyond the treated unit.
Relatively few opportunities were found to test the hypothesis that fuel treatment activities have consequences for fire behavior beyond their perimeters. But fire severity was significantly greater behind ineffective treatments (those where fire severity was greater than in adjacent untreated comparison plots), than in adjacent 'unprotected' areas. Likewise, fire severity was somewhat less behind effective fuel treatments than in adjacent unprotected areas, though this result was not statistically significant.

Effective fuel treatments may increase native plant richness and inhibit post-wildfire establishment of non-native species.
Wildfire consumption of canopy cover and surface litter was significantly correlated to decreases in native plant species and increases in non-native plant species, at least in the first post-fire year. While we found some evidence that fuel treatments themselves may also promote non-native species, the effects of severe wildfire were more significant. Fuel treatments that effectively reduce wildfire severity therefore may also reduce the risk of post-fire invasion by non-native plants.

Cover Photos

Cover photos are of treated and untreated plot pairs. The top pair is from the 2005 Power fire on the Eldorado National Forest, the middle pair is from the 2004 Aspen fire on the Coronado National Forest, and the bottom pair is from the 2004 Davis fire on the Deschutes National Forest.

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1 Project Backround

1.1 Rationale

Fuel treatment effectiveness as a pre-suppression strategy is a controversial tenet of wildfire management with a strong theoretical foundation, but scant empirical evaluation. Several recent reviews provide a survey of the extant literature on the scientific justification for fuel treatment programs (Peterson et al. 2005; Graham et al. 2004; Carey and Schumann 2003; Fernandes and Botelho 2003). A perusal of the publications cited in these reviews reveals that much of the evidence of fuel treatment effectiveness comes from the results of simulations based on models of fire spread (Rothermel 1972) and crown fire potential (Rothermel 1991; Van Wagner 1977). But the ability of current fire behavior models to reflect reality has received little validation, particularly under the extreme conditions that produce large wildfire events (Cruz et al. 2005). Thus, the results of modeling experiments are perhaps best viewed as hypotheses awaiting an empirical test.

Given the obvious limitations on experimentation with actual wildfires, empirical evidence of fuel treatment effectiveness relies primarily on natural experiments in which an actual wildfire serendipitously encounters one or more fuel treatment areas. Though there have been recent efforts to collect fire behavior data *in situ* as wildfires encounter fuel treatments (Fites and Henson 2004), all results published to date from such natural experiments have relied on *post facto* analysis. Only five of these studies (Skinner and others *in press*; Cram et al. 2006; Martinson and Omi 2006; Raymond and Peterson 2005; Pollet and Omi 2002) included both a statistical test and an explicit attempt to control for the influences of topography and weather, which along with fuels are the determinants of fire behavior. Among these five studies there is no disagreement that treatment of surface fuels effectively mitigates wildfire impacts. However, the effectiveness of canopy treatments that involve forest thinning is less certain, particularly when fuels resulting from the canopy treatment are left untreated on site.

Fuel treatments do have the potential to compound wildfire hazards. Crown fuel reduction exposes surface fuels to increased solar radiation, which would be expected to lower fuel moisture content and promote production of fine herbaceous fuels (Agee 1996). Surface fuels may also be exposed to intensified wind fields, accelerating both desiccation and heat transfer. Treatments that include prescribed burning may increase nutrient availability (Covington et al. 1997; Kaye and Hart 1998; Gundale et al. 2005) and further stimulate production of fine fuels. All these factors facilitate the combustion process, increase rates of heat release, and exacerbate surface fire intensity (Agee 1996).

Fuel treatment application may also result in other unintended consequences, such as introduction of non-native species. Fuel treatments that increase the availability of light, water, and nutrients can favor spread of non-native species (Hobbs and Huenneke 1992; Stohlgren et al. 1999; Brooks 2003). In addition, unseen non-native seeds may be carried with humans and mechanical equipment used in fuel reduction treatments. This can essentially increase the propagule pressure of non-native species in an area, which has also been shown to be an important factor in predicting successful non-native plant

invasions (D'Antonio et al. 2001; Lockwood et al. 2005). Mechanical equipment can also cause soil disturbances that favor non-native plant establishment (Hobbs and Huenneke 1992; Kotanen 1997). Based on the known effects of fuel treatments on ecosystem structure and processes, there is potential for non-native species to thrive in areas treated for fuels reduction (Sieg et al. 2003). Given the uncertain benefits and potential negative consequences of fuel treatment activities, land managers would be assisted by additional empirical information on the outcomes from fuel treatments tested by wildfire.

1.2 Objectives

The goal of this research was to assess the effectiveness of pre-fire management activities for mitigating wildfire damages, including those associated with non-native plant invasion. We sampled five large wildfires in montane coniferous forests in the states of Colorado, Arizona, California, Oregon, and Washington to meet the following objectives in support of our research goal:

- Compare stand conditions between areas that received pre-fire fuel treatment and adjacent untreated controls.
- Compare wildfire severity between areas that received pre-fire fuel treatment and adjacent untreated controls.
- Relate non-native plant cover to fire severity and management activities.
- Increase the diversity of ecosystems and geographic locations represented in studies of pre-fire treatments to improve generalizations regarding their effectiveness.

1.3 Hypotheses

We tested four null hypotheses based on our stated objectives:

H_{o1}:   Pre-fire fuel treatments do not increase stand resistance to crown fire, as indicated by average tree size, height to canopy, and stand density.

H_{o2}:   Pre-fire fuel treatments do not reduce wildfire intensity/severity, as indicated by scorch height, crown volume scorch and consumption, and ground char depth.

H_{o3}:   Pre-fire fuel treatments are not associated with greater non-native plant cover than untreated areas.

H_{o4}:   There is no relationship between fire severity and non-native plant cover.

1.4 Deliverables

The proposed deliverables for this project included annual progress reports and this final report, in addition to multiple publications and presentations. Table 1 lists the proposed deliverables and the method of product delivery.

Table 1. Products proposed and delivered by this project.

Proposed Deliverables	Product Delivery
Annual progress reports	Written summaries delivered to JFSP Program Manager in September 2005 and 2006.
Final report	Delivered to the JFSP Governing Board on December 31, 2006.
Publications	See Appendix A for citations: 1 paper in published proceedings. 1 chapter in a US Forest Service General Technical Report. 1 master's thesis. 2 papers submitted to peer-reviewed journals.
Presentations	See Appendix A for presentation titles and venues: 2 invited presentations at agency workshops 6 contributed presentations at national conferences 1 special session organized for a national conference
Field Demonstrations	4 field demonstrations for study site managers.
Web site to house final report.	http://www.cnr.colostate.edu/frws/research/

2 Methods

This research investigated the severity of recent wildfires that crossed existing fuel treatment boundaries and subsequent abundance of non-native plant species. Identification and selection of study sites, assessment of forest conditions and fire severity, botanical surveys, and data analyses were the major activities associated with this project.

2.1 Study Site Selection

We remained informed of large wildfire incidents in 2003 and 2004 through regular review of the National Incident Management Situation Report provided online by the National Interagency Fire Center at *http://www.cidi.org/wildfire/fire.htm*. We initiated contact with fire managers on all districts affected by a wildfire that exceeded 4,000 ha (10,000 acres) in size, since these large wildfires are most likely to include multiple treatment areas and are indicative of weather conditions extreme enough to provide an adequate test of treatment effectiveness.

Upon identification, potential study sites were subjected to the following set of preliminary selection criteria via phone interview with appropriate personnel:

- A 2003 or 2004 wildfire included both treated and untreated areas within its perimeter. Treatments within the last 10 years received priority consideration. Areas were defined as "untreated" where there was no record of management activity.
- Stand treatment histories were documented and available.
- Major suppression activities that may have impeded fire spread did not take place in proximity to the potential study sites.
- Salvage activities had not taken place and were not scheduled to occur prior to our availability for a site visit.
- Spatial information was available that included compatible maps of the fire perimeter and progression, treatment areas, topography, vegetation types, roads, and planned salvage activities.

Appropriate maps and treatment documentation were requested for sites that passed these preliminary criteria. Upon receipt, a second set of criteria were applied through review of the stand treatment maps and histories:

- At least 3 burned treatment areas were adjacent to and lee (with respect to the direction of fire spread) of topographically similar burned but untreated areas.
- A major road or drainage that may have impeded fire spread did not separate the treated and untreated areas to be sampled.
- Treatment areas could accommodate multiple plots with a 50m buffer between plots and treatment edges.

We identified 99 wildfires that exceeded 4,000 ha in 2003 (64 wildfires greater than 4,000 ha) and 2004 (35 wildfires greater than 4,000 ha). Eight 2003 wildfires and seven 2004 wildfires included areas of pre-fire fuel treatments and met our initial selection criteria. We selected for sampling the two fires from each year that provided the greatest

extent and variety of fuel treatment areas. Additionally, we included the 2002 Hayman fire as a study site for this project, though sampling occurred prior to receipt of funds. We were in the process of sampling the Hayman fire in 2003 to meet objectives for another project and decided to add plots for this project since the fire otherwise met our selection criteria.

2.2 Study Areas

In addition to the 2002 Hayman fire in Colorado, the wildfires chosen as our study areas for this research were the 2003 Aspen fire in Arizona, the 2003 Davis fire in Oregon, the 2004 Power fire in California, and the 2004 Fischer fire in Washington. The locations of these fires are depicted in Figure 1 and a summary of study site characteristics is provided in Table 2.
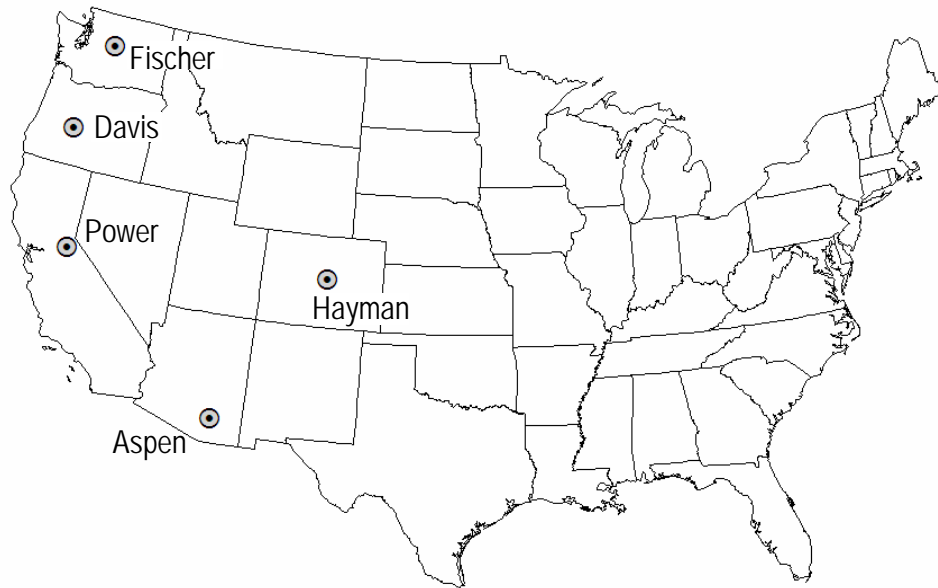

Figure 1. Locations of wildfires sampled in this study

Table 2. Summary of study site characteristics.

	Hayman	Aspen	Davis	Fischer	Power
Start Date	6-8-2002	6-17-2003	6-28-2003	8-8-2004	10-6-2004
Location	Park County, Colorado	Pima County, Arizona	Deschutes County, Oregon	Chelan County, Washington	Amador County, California
Administrative Unit	Pike National Forest	Coronado National Forest	Deschutes National Forest	Wenatchee National Forest	Eldorado National Forest
Latitude (ºN)	39.1099	32.4082	43.6158	47.5908	38.5004
Longitude (ºW)	105.2891	110.7385	121.7757	120.5520	120.2972
Fire Size (ha)	56,000	37,000	8,500	6,650	6,800
Area Treated (ha)	8,000	312	960	148	1,125
Age of surface treatments (yr)	1, 10-13	~ 7	n/a	n/a	10, 15-20
Age of canopy treatments (yr)	2	~ 7	<1, 2	n/a	1, 5
Age of combination treatments (yr)	1, 9-10	n/a	0-2	1	n/a
Vegetation	Ponderosa pine Douglas-fir	Ponderosa pine White fir Live oak	Ponderosa pine White fir	Ponderosa pine	Jeffrey pine Incense cedar White fir
Elevation (m)	2,000-2,700	2,000-2,400	1,400-1,900	500-1,200	1,200-2,000
Nearest Weather Station [a]	Bailey	Rincon	Black Rock	Dry Creek	Beaver
Distance to Weather Station (km)	13.4	24.3	8.0	12.8	<1.0
Elevation of Weather Station (m)	2,438	2,511	1,487	1,060	1,737
Minimum Relative Humidity (%)	17	5	8	12	1
Maximum Temperature (ºF)	79	86	93	97	87
Maximum Average Windspeed (MPH)	15	10	10	7	4
Burning Index (%) [b]	96	99	96	72	84

Notes:

[a] Weather statistics represent the most extreme conditions during the period when sampled fuel treatments were encountered by wildfire (see Figures 2 through 6).

[b] Burning Index is a component of the National Fire Danger Rating System and is an indicator of potential wildfire behavior. The statistic reported represents the average percentile of the historic distribution of Burning Indexes recorded for the dates on which sampled treatments were encountered by wildfire. Burning Index percentiles were calculated with Fire Family Plus software (USDA Forest Service 2000).

2.2.1 Hayman Fire

The Hayman fire ignited on June 8, 2002, from an illegal camp fire on the Pike National Forest in Park County, Colorado, approximately 10 km northwest of Lake George. The fire remained active until June 27, by which time it had burned 56,000 ha and spread into three additional counties (Teller, Jefferson, and Douglas). Approximately one-third of the
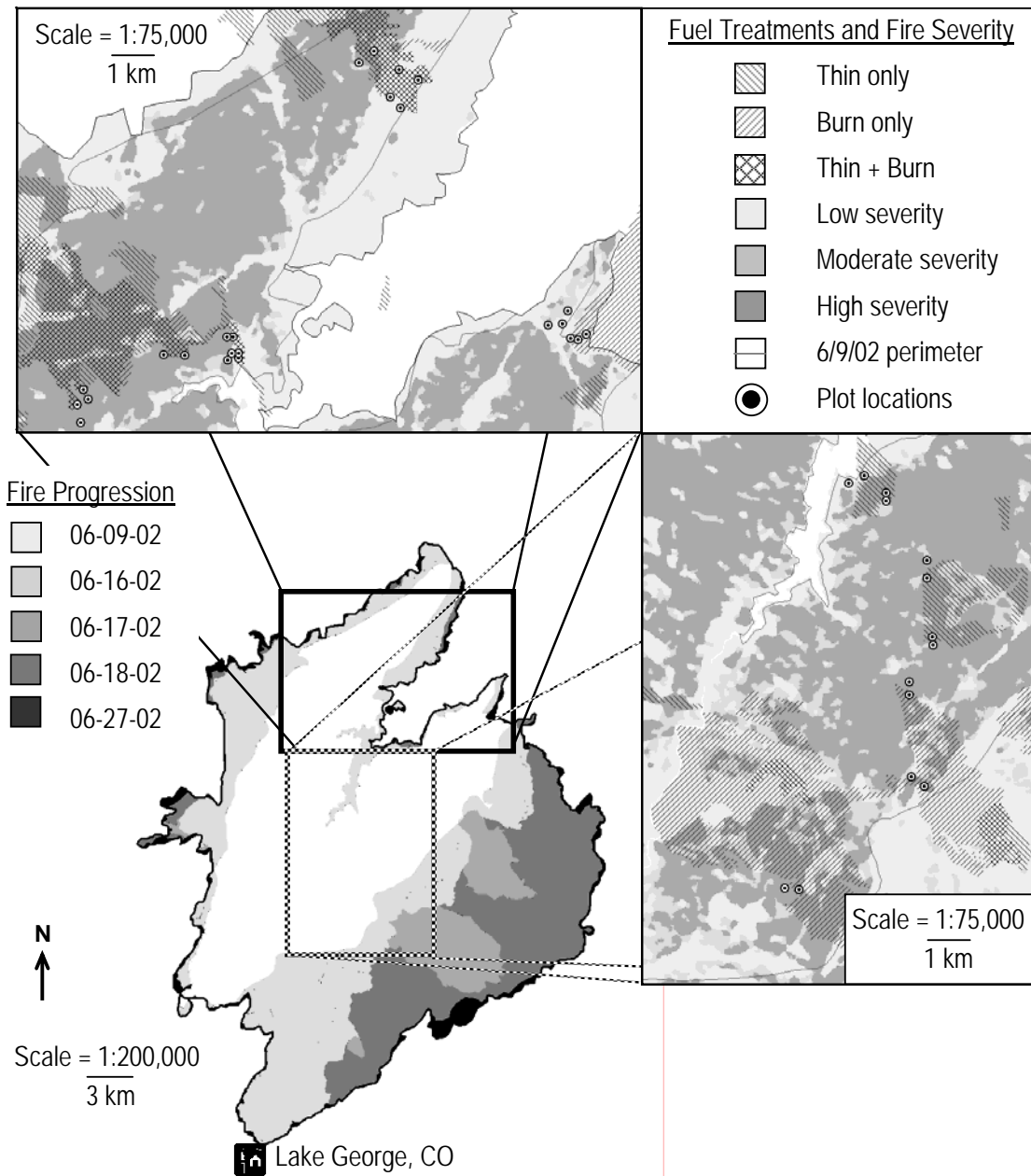
Figure 2. Progression of the Hayman fire, fire severity and fuel treatment units within our study area, and our plot locations. Spatial information provided by the Pike National Forest.

area burned on a single day (June 9) under strong southwesterly winds. Fire spread forked around both sides of Cheesman Reservoir and the June 9 perimeter is coincident with the boundaries of previous fires in a number of locations, including the 2001 Polehemus prescribed burn and the May 2002 Schoonover wildfire (see Finney et al. 2003 for a complete discussion). Winds shifted on subsequent days, pushing the fire to the southeast, with June 17 and 18 accounting for most of the remaining burned area. Elevation ranges from 2,000 m to 2,700 m throughout the burn area, but rises dramatically in the Lost Creek Wilderness on the fire's western perimeter. Slopes are moderately steep with most ranging between 20 and 40 percent. Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menzisii*) are dominant in the canopy with lodgepole pine (*Pinus contorta*) also present.

Management activities had occurred on approximately 8,000 ha within the burn area, though we focused on the prescribed fire and mechanical thinning activities implemented after 1990 that were encountered by the Hayman fire on June 9. These included 1,600 ha prescribe-burned between 1989 and 1992, 36 ha of the 2001 Polehemus prescribed burn, 525 ha that were thinned between 1995 and 2001 without subsequent treatment of activity fuels, 400 ha that were thinned between 1989 and 1992 with slash removed or burned between 1992 and 1993, and 28 ha that were thinned with slash piled and burned in 2001. Figure 2 depicts a map of the fire perimeter, treatment area, and plot locations. We sampled these areas in August 2003.

2.2.2   Aspen Fire
The Aspen fire was ignited by lightning on June 17, 2003 in the Wilderness of Rocks on the Coronado National Forest about 20 km northeast of Tucson, AZ. Strong southerly winds on the 19th pushed the fire out of the Wilderness and resulted in a 6 km run that burned through the town of Summerhaven and the Mount Lemmon observatory. During the next several days the fire burned over several small thinning units that had been installed two years previously to help protect the town and observatory. The fire also burned to the western edge of the 2002 Bullock wildfire defined by the General Hitchcock Highway and Gracie Ridge on the east side of the Butterfly Peak Natural Area. A wind shift on July 4 caused the fire to spread toward the southwest and enter several areas along the Highway that were prescribed burned in the mid-1990's. The fire continued to grow to a final size of 37,000 ha until containment on July 12, 2003.

Topography in the study area is highly complex with most slopes exceeding 35 percent. Elevation ranges from 2,000 m to 2,400 m in the areas that were prescribe-burned and from 2,400 m to 2,700 m in the areas that were thinned. Topographic and administrative constraints limited the areas available for treatment activities. The area of completed prescribed burn units totaled 185 ha, while the area of thinned units totaled 127 ha. Vegetation is primarily ponderosa pine forest, transitioning to Douglas-fir at higher elevations. Figure 3 depicts a map of the fire severity, fire progression, treatment areas, and plot locations. Data were collected in June 2004.

Fire Progression

	20030617
	20030617
	20030618
	20030619
	20030620
	20030621
	20030622
	20030623
	20030624
	20030625
	20030626
	20030627
	20030628
	20030629
	20030630
	20030702
	20030703
	20030704
	20030705
	20030706
	20030707
	20030708
	20030709
	20030710

Scale = 1:50,000 / 1 km

Summerhaven, AZ

Fuel Treatments and Fire Severity

- Burn
- Thin
- Low severity
- Moderate severity
- High severity
- Fire progression contour
- ◉ Paired treatment plots
- ● Unburned control plots
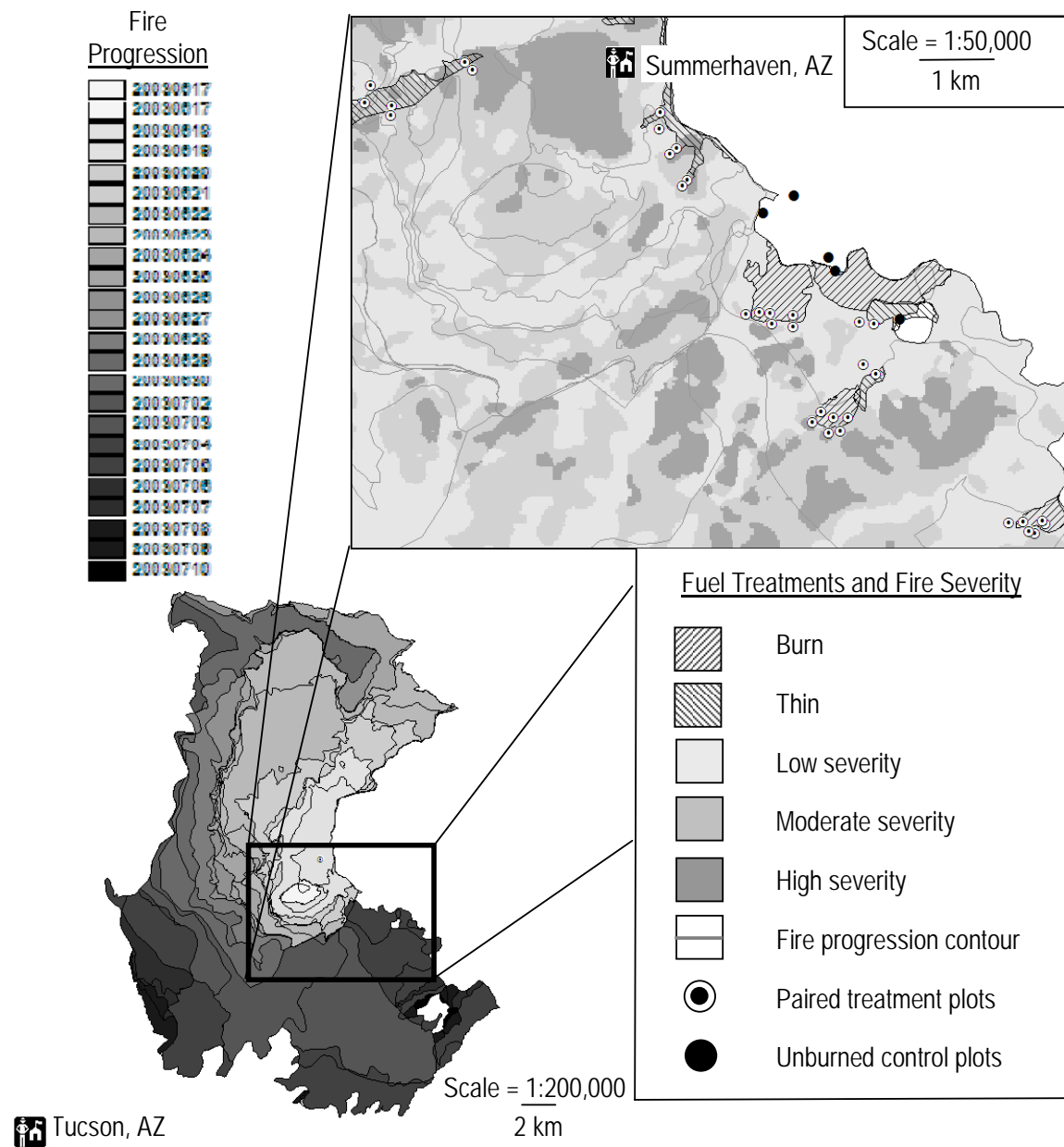
Scale = 1:200,000 / 2 km

Tucson, AZ

Figure 3. Progression of the Aspen fire, fire severity and fuel treatment units within our study area, and our plot locations. Spatial information provided by the Coronado National Forest.

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2.2.3 Davis Fire

The Davis fire started from an undetermined human source on June 28, 2003 in the Deschutes National Forest, about 30 km southwest of La Pine, OR. The fire developed two heads as it burned around Davis Lake on June 29. Southwesterly winds in excess of 25 miles-per-hour on June 29 and 30 resulted in the most active burning days when nearly 75 percent of the fire's 8,500 ha burned. Further fire growth was impeded largely by the Wickiup Reservoir and barren lava flows along the fire's eastern perimeter. Topography is dominated by the dome-shaped Davis Mountain in the middle of the burn area. Slopes are generally gentle and rarely exceed 15 percent. Elevation ranges from 1,300 m at Davis Lake to 2,000 m at the top of Davis Mountain. Dry mixed conifer forest is the primary vegetation community in the burn area. Ponderosa pine and white fir (*Abies concolor*) are the most common tree species, with lodgepole pine, sugar pine (*Pinus lambertina*), western white pine (*Pinus monticola*), red fir (*Abies magnifica*) noble fir (*Abies procera*), and Douglas fir also represented.

Silvicultural treatments had occurred throughout the burn area prior to the wildfire (Figure 4). Most of the treatments implemented prior to 1990 were shelterwoods, while more recent treatments focused on low thinning to increase fire resistance. We restricted our sampling to these latter treatments, which included 109 ha that received a single entry thinning in 2000 or 2001, 229 ha that received two thinning entries between 2001 and 2003, 72 ha that received two thinning entries between 2000 and 2001 with slash piled between 2002 and 2003, and 54 ha that received two thinning entries between 2000 and 2001 with slash yarded and burned in 2001. Figure 4 depicts a map of the fire severity, fire progression, treatment areas, and plot locations. Data were collected in July 2004.

2.2.4 Fischer Fire

The Fischer fire started on August 8, 2004 on private land in Chelan County about 7 km east of Leavenworth, WA. The source of the ignition was a motorcycle without a spark arrester. Over the next several days the fire spread up Fischer canyon and across both sides of a ridge that separates the Williams and Derby canyons in the Wenatchee National Forest. The Forest Service had administered commercial thinnings on 148 ha along this ridge that were completed in 2001, followed by piling and burning of the slash between 2002 and 2003. The fire continued to grow until August 21, when it reached a final size of 6,650 ha. The fire resulted in the evacuation of 400 homes, one of which was destroyed.

Topography in the study area is highly complex with most slopes exceeding 35 percent. Elevation in the sampled areas ranges between 500 m and 1,200 m. Ponderosa pine is the dominant tree species with some Douglas-fir present at higher elevations. Figure 5 depicts a map of the fire severity, treatment areas, and plot locations. Data were collected in July and August 2005.
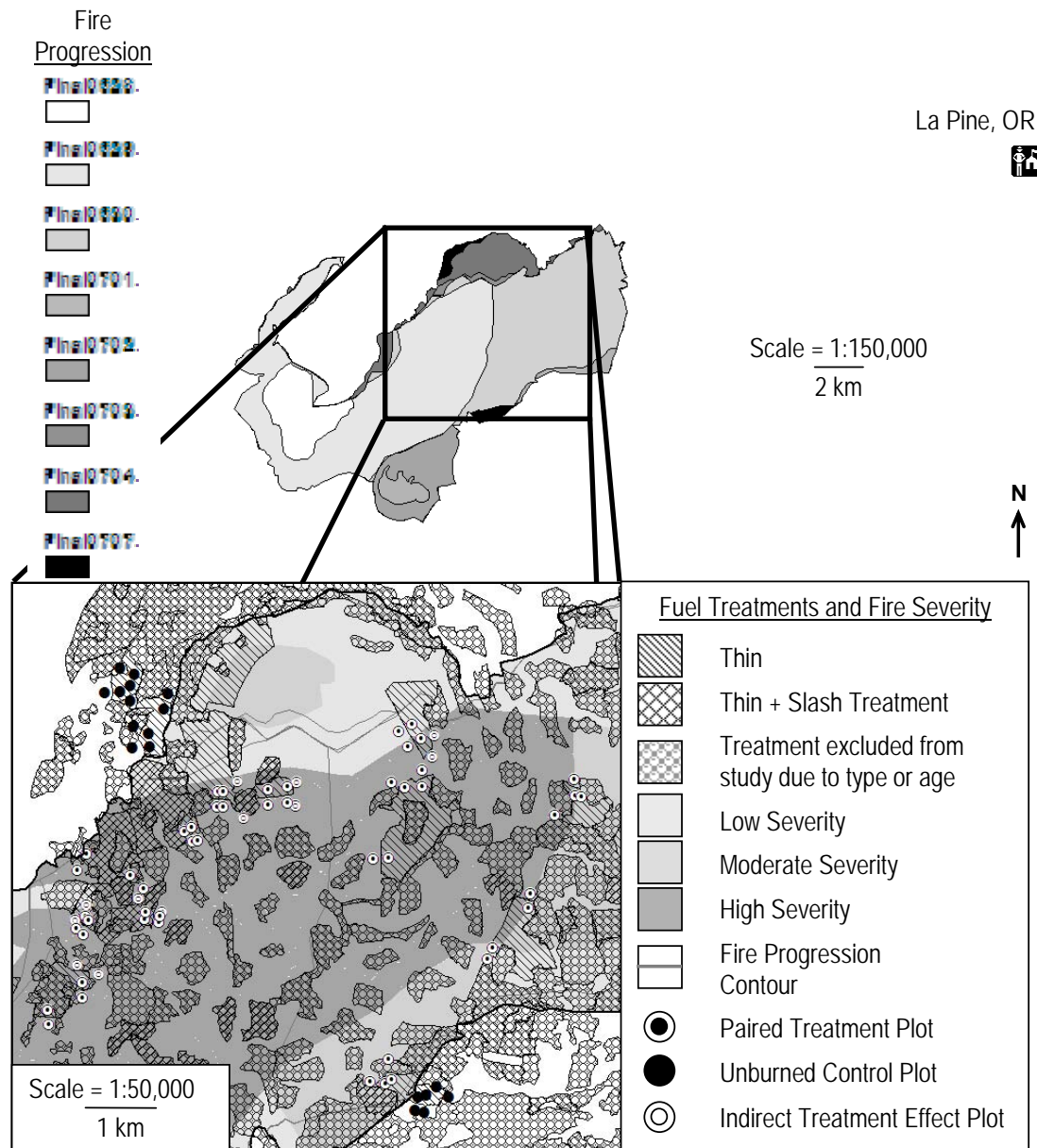
Figure 4. Progression of the Davis fire, fire severity and fuel treatment units within our study area, and our plot locations. Spatial information provided by the Deschutes National Forest.

N

Leavenworth, WA

Scale = 1:100,000
2 km

Fire Progression

Fuel Treatments and Fire Severity

Thin + Slash Treatment
Low Severity
Moderate Severity
High Severity
Fire Progression Contour
Paired Treatment Plot
Unburned Control Plot

Scale = 1:36,000
1 km

Figure 5. Progression of the Fischer fire, fire severity and fuel treatment units within our study area, and our plot locations. Spatial information provided by the Wenatchee National Forest.
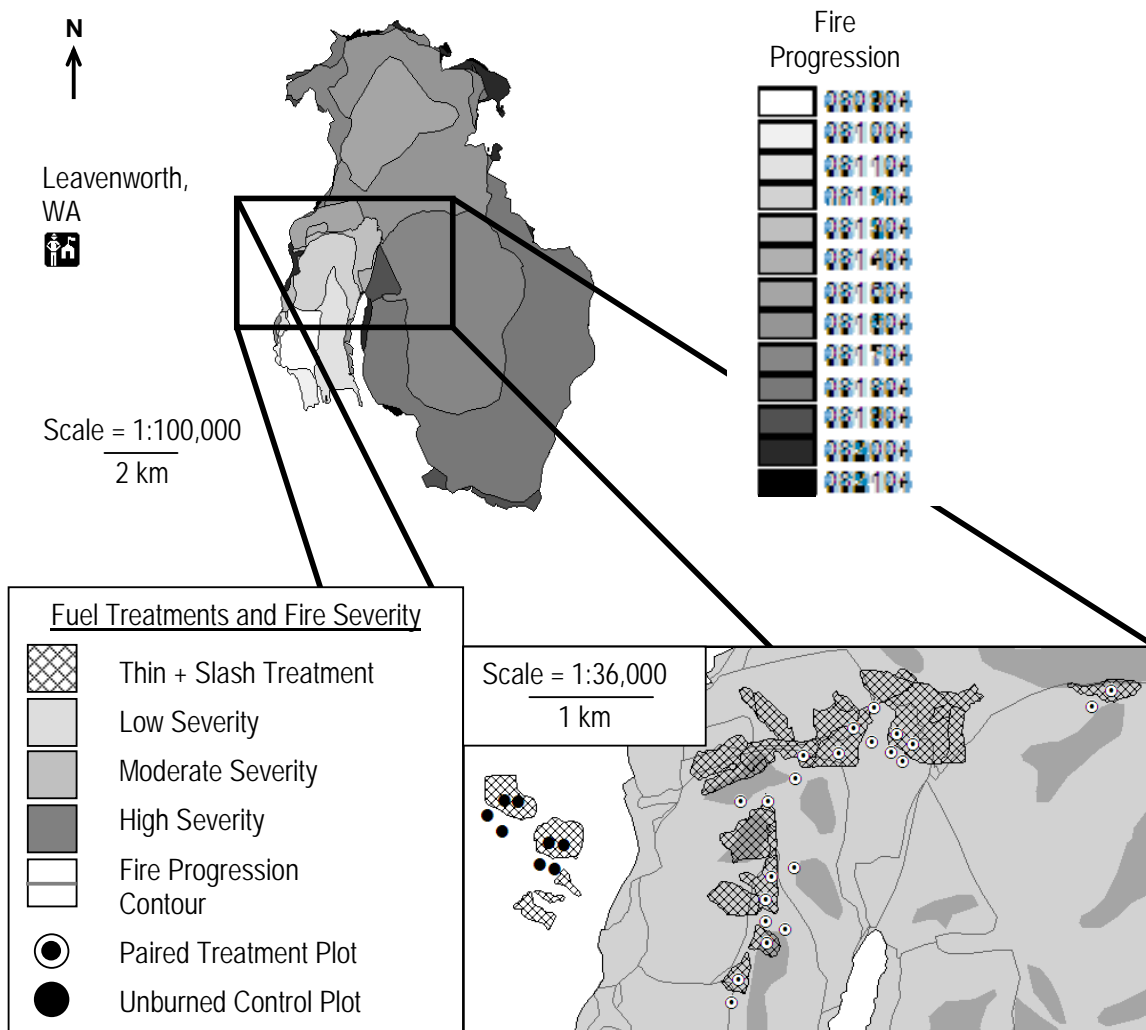
2.2.5 *Power Fire*

The Power fire started on October 6, 2004 from an undetermined ignition source in the Eldorado National Forest approximately 30 km east of Pioneer, CA. The fire exhibited little growth until October 12 when strong easterly winds expanded the perimeter 14 km westward over a three day period along the north side of the Mokelumne River. The fire grew to a final size of 6,800 ha before being contained on October 21. Elevation in the area rises from 1,200 m at the river to over 2,000 m around Bear Lake Reservoir. Slopes
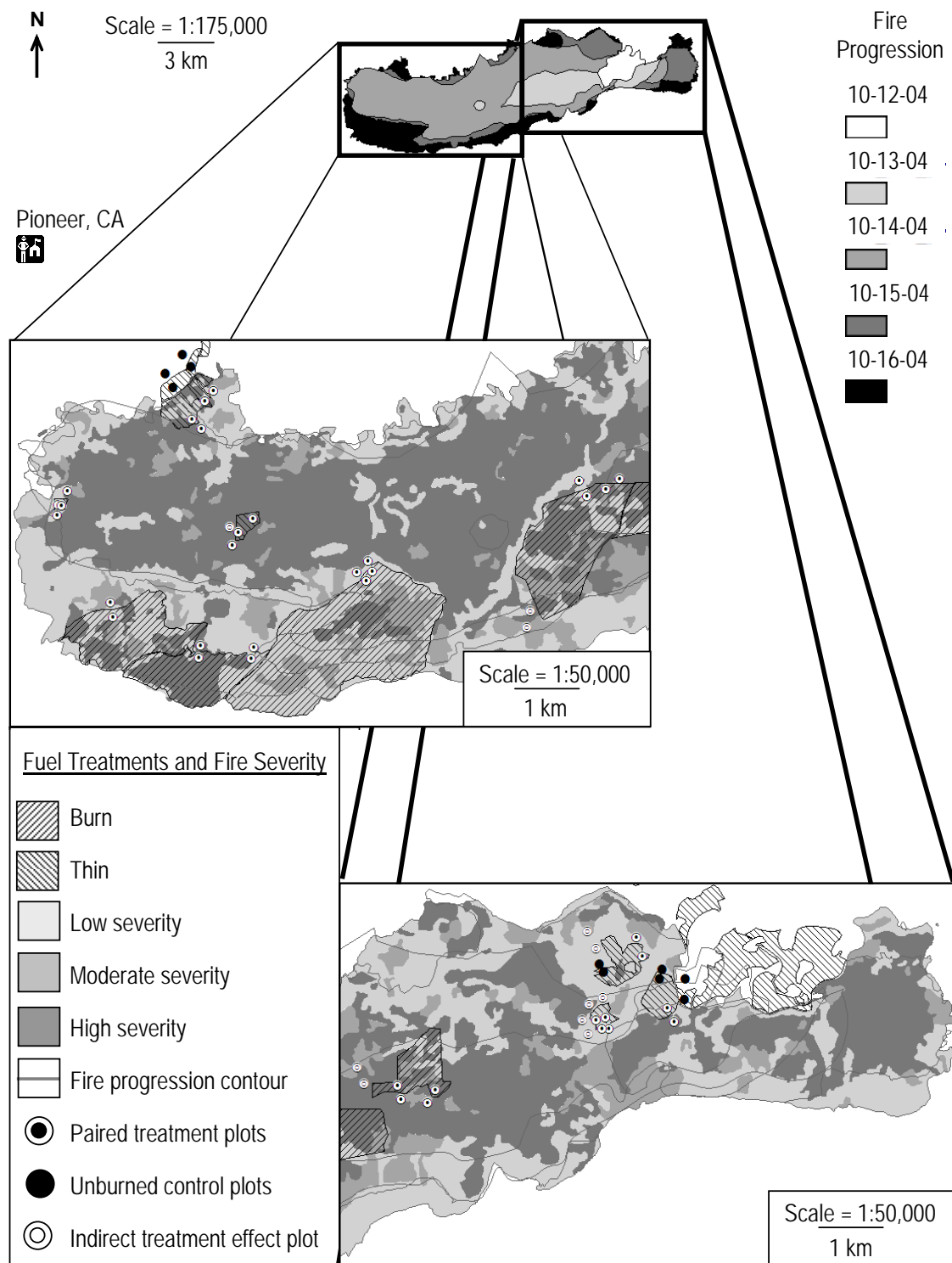
Figure 6. Progression of the Power fire, fire severity and fuel treatment units within our study area, and our plot locations. Spatial information provided by the Eldorado National Forest.

are generally south-facing and moderately steep, with most ranging between 15 and 35 percent. Vegetation in the burn area transitions from jeffrey pine (*Pinus jeffreyii*) and incense cedar (*Calocedus decurrens*) at lower elevations to red fir and white fir at higher elevations.

Treatments encountered by the Power fire included several areas that were either thinned or prescribe-burned. These included 675 ha that were burned about 10 years prior to the wildfire and 335 ha that were burned 15 to 20 years prior to the wildfire. The thinning units included 75 ha that were one year old and 40 ha that were five yeas old when affected by the Power fire. Figure 6 depicts a map of the fire severity, treatment areas, and plot locations. Data were collected in June and July 2005.

2.3   Sampling Design
Plot locations were determined in advance of field visitation based on maps of wildfire and fuel treatment perimeters provided by land managers. Plots were subjectively placed such that treated and untreated pairs were on similar slope and aspect with no barriers to fire spread between them. Treated and untreated comparison plots were separated by no more than 200 m to minimize differences in weather and site conditions. Edge effects were avoided by insuring a 50 m buffer between plots and treatment perimeters. A final consideration in plot placement was the direction of fire spread; plots were placed such that fire entry into the untreated site would have been prior to, or simultaneous with, entry into the treated site. These precautions in plot placement were critical due to the numerous topographic and climatic factors that may interact with fuels to produce wide variability in fire behavior and effects within large wildfires, as evidenced in Figures 2 through 6. However, to avoid bias in our sampling design, the remotely derived fire severity maps depicted in Figures 2 through 6 were not considered in plot placement. Thus, our sampling design insured that any observed differences in wildfire severity between treated and untreated plots could be reasonably attributed to modified fuel conditions, rather than some other confounding influence. Where possible, the "value-added" benefit of fuel treatments for protecting adjacent untreated areas was assessed by sampling in untreated areas immediately behind treatments (with respect to the direction of fire spread) paired with plots in adjacent untreated areas unprotected by treatment.

2.4   Data Collection and Analysis
At each sampling location we established a variable radius plot defined with an angle gauge for overstory measurements, centered within a 100-m^2 fixed area Nested Intensity plot (Barnett and Stohlgren 2003) for understory measurements. The Nested Intensity plot is multi-scale and has nested within it one 10-m^2 subplot and four 1-m^2 quadrats. Our sampling objectives focused on re-construction of pre-fire stand conditions, assessment of fire severity, and cover estimation for all vascular plant species present post-fire.

2.4.1   Stand Structure
Pre-fire stand conditions were reconstructed from trees within variable radius plots defined by a Cruiser's Crutch using a basal area factor sufficient to sample 10 to 15 trees

(Avery and Burkhart 2002). Since variable radius plots are inaccurate for small trees (Stage and Rennie 1994), trees less than 10 cm in diameter were tallied separately within the fixed area 100-m^2 Nested-Intensity plot. Measured variables included position in canopy, species, tree height, tree diameter, height to the pre-fire live crown, stand density, and basal area. Each tree's position in the canopy was rated as dominant, co-dominant, intermediate, or suppressed. Heights were calculated trigonometrically from clinometer readings. Tree diameters were measured with metric diameter tape 1.4 m above ground on the uphill side. Lower tree boles were inspected carefully for evidence of consumed branches to avoid over-estimating crown base heights in severely burned stands. Effective canopy base height was calculated for analyses as the lower limit of the lowest 1-ft horizontal section of the canopy in which canopy bulk density exceeded 0.037 kg/m^3 (Scott and Reinhardt 2001). Canopy bulk density was calculated with the maximum running mean method recommended by Scott and Reinhardt (2001) using Brown's (1978) allometric equations for crown weights contributed by needles and fine twigs. Comparisons between treated and untreated stand conditions were analyzed with one-tailed paired t-tests.

2.4.2   Fire Severity
We evaluated wildfire severity at each plot in terms of stand damage, as well as upward and downward heat pulse components. Stand damage was rated as follows (after Omi and Kalabokidis 1991):

   0: No damage – all tree crowns unscorched.
   1: Spotty damage –partial scorch on at least 1 tree, but some trees unscorched.
   2: Moderate damage – partial scorch on all tree crowns, but few trees completely
        scorched.
   3: Heavy damage – nearly all tree crowns completely scorched, but few crowns
        consumed.
   4: Extreme damage – nearly all tree crowns consumed.

The downward heat pulse was estimated with ground char ratings assigned to each of the four 1-m^2 quadrats within the Nested Intensity plot. Ground char was rated as follows (after Ryan and Noste 1985):

   0: Unburned - no evidence of char.
   1: Light – leaves and twigs charred.
   2: Moderate - all twigs, leaves, and standing grasses consumed, logs charred.
   3: Deep – large fuels partially consumed, mineral soil altered in color or texture.

Since the entire range of ground char ratings may be represented over short distances, we measured the distance from the center of each quadrat to the nearest particle representing each ground char class, within a 5 m search radius. We extended our search beyond the 1-m^2 quadrats to increase the likelihood of considering large fuel particles, which tend to be the most sensitive and reliable indicators of soil heating. Inverse distance weighting was then used to calculate an average ground char rating for each 1-m^2 quadrat with the

minimum distance set to 1 m (i.e., all particles within 1 m of the quadrat received equal and greatest weight).

The height of needle scorch on the coniferous trees sampled at each plot was measured as an indicator of fireline intensity (Van Wagner 1973). Since height of needle scorch underestimates fireline intensity on trees that are either unscorched or completely scorched (i.e., the upper bound of scorch height is limited by tree height, while the lower bound is limited by crown base height), we employed Martinson and Omi's (2006) method for calculating average scorch height at each plot. Percent canopy scorch and consumption was ocularly estimated on all trees, as well. We focused on the sum of percent scorch and consumption as our primary response variable, since this has proved to be the most sensitive indicator of fuel treatment effectiveness in our previous studies. Data were analyzed with two-tailed paired t-tests. Percentage data were arcsin transformed (Zar 1984) to meet parametric assumptions.

2.4.3   Floristics
Botanists identified and estimated the cover of all species in each 1-m^2 subplot. Cover was also recorded for any non-plant surface items encountered. Species with less than 1% cover were recorded as 0.5% cover. Species cover values were averaged from the four 1-m^2 subplots and did not include tree canopy cover or dead vegetation. However, canopy closure over the plot as a whole was estimated using a spherical densitometer. Eight densitometer readings were taken and averaged at each plot by facing each of the four cardinal directions at two points on the perimeter of the 100-m^2 plot, i.e. the midpoints of the 5 m axes. Botanists then searched the 10-m^2, and 100-m^2 plots for any species not previously recorded and noted them as present. Plants that could not be identified to species were collected off-plot and pressed for later identification at the Colorado State University herbarium. We recorded species as either native or non-native in accordance with the Natural Resources Conservation Service PLANTS database (USDA 2006). We performed analysis of variance (ANOVA) to determine site, treatment, and wildfire effects on native and non-native richness and cover. Prior to analysis, we transformed nonnormal environmental data using either log or square root transformations.

Additionally, soils were analyzed for indicators of nutrient (carbon and nitrogen) and moisture (texture) availability for possible correlations to non-native abundance. Samples were collected from the corners and center of the 100-m^2 plot to a depth of 5 cm and pooled into one composite sample for each plot, which were then air-dried for at least 48 h and sieved to 2-mm. Soil texture was analyzed using an ASTM 152H-Type hydrometer (Gee and Bauder 1979). Samples were then ground to a fine powder, oven-dried at 55°C for 48 h and analyzed for percent total carbon and nitrogen using a LECO-1000 CHN analyzer (LECO Corporation, Saint Joseph, Missouri, USA). We measured available phosphorus with a multi-element extractant using the Mehlich 3 method (Mehlich 1984).

3 *Results and Discussion*

The results from this study add substantially to the extant literature on fuel treatment effects on subsequent wildfire severity and initial response by non-native plants. Most previous empirical studies of fuel treatment effectiveness included field sampling of just one treated unit (e.g., Martinson and Omi 2006; Pollet and Omi 2002; Wagle and Eakle 1979). While all such previous studies agree that fuel treatments mitigate wildfire damages, they offer little insight into how treatment effectiveness varies by type, intensity, and age.

Previous studies that did sample more than one unit were generally landscape assessments (e.g., Finney et al. 2005; Oucalt and Wade 2004; Martinson et al. 2003; Weatherspoon and Skinner 1995) that relied primarily on remotely sensed information. While such methods have the advantage of complete coverage, inferences regarding treatment effectiveness from such studies are compromised by the numerous confounding influences on wildfire behavior associated with changes in fuels, topography and weather over space and time.

Our results are most comparable to four recent studies that employed field sampling across the boundaries of multiple treatment units of various types (Skinner et al. *in press*; Cram et al. 2006; Raymond and Peterson 2005; Omi and Martinson 2002). All these studies found thinning followed by slash treatment to effectively reduce wildfire severity (as measured by percent crown scorch or mortality), while thinning alone was ineffective. Omi and Martinson (2002) suggest that prescribed burns in the absence of thinning can also be effective. Results from this study are in agreement with these generalities. However, the results presented in this report are unique in that they also address the influence of treatment age on effectiveness, a variable that has heretofore received little scientific inquiry.

3.1 Stand Conditions

Averaged across all sites and treatments, the treated areas we sampled generally had fewer trees (484 trees/ha vs. 1,110 trees/ha in adjacent untreated areas), with lower crown bulk densities (0.07 kg/m^3 vs. 0.10 kg/m^3 in adjacent untreated areas), higher crown bases (8.0 m vs. 4.1 m in adjacent untreated areas), and larger diameters (38.4 cm vs. 28.6 cm in adjacent untreated areas).

Among treatment types (i.e., surface treatments such as broadcast burns, canopy treatments such as pre-commercial thins, and combination treatments that included a canopy treatment followed by a surface treatment), those that focused on reducing canopy fuels resulted in the greatest reductions in stand density (791 trees/ha vs. 477 trees/ha and 474 trees/ha for surface and combination treatments, respectively) and canopy bulk density (0.05 kg/m^3 vs. 0.04 kg/m^3 and 0.02 kg/m^3 for combination and surface treatments, respectively), as well as the greatest increase in mean tree diameter (13.1 cm vs. 7.9 cm and 5.6 cm in surface and combination treatments, respectively). However, treatments that focused on surface fuels resulted in the greatest rise in height to canopy (4.8 m vs. 3.7 m in combination treatments and 3.5 m in canopy treatments).

But the degree to which stand conditions were altered by fuel treatments varied among our five study sites. Differences between treated and untreated areas in stand conditions were most significant in thinned areas of the Davis fire (Table 3). All treatments within the Fischer and Power fire also effectively reduced canopy fuels. However, no significant changes in stand conditions were observed among any of the treatments in the Hayman and Aspen fires.

3.2   Fire Severity

Most of the treatments we sampled reduced wildfire severity to some degree. Trees in untreated plots were completely scorched with an additional 15 percent of needle consumption, on average, while trees in treated plots averaged 80 percent crown scorch. But treatment effectiveness varied considerably by type and age. The greatest statistical significance was found among the most recent (less than one year old) pre-commercial thins in the Davis fire (Table 4). While these treatments managed to reduce canopy consumption, they failed to save the trees, as crown scorch was still complete. Thin-only treatments at other sites were generally ineffective. Thin-only treatments in the Hayman and Aspen fires were actually affected more severely than adjacent untreated areas, though the differences were not significant. Also, treatments more than nine years old were not found to have a significant effect on fire severity at any site, regardless of treatment type.

However, recent (less than 10 years old) treatments that included reduction of surface fuels were generally effective, with or without prior treatment of canopy fuels. But thinning followed by slash treatment at the Hayman and Davis sites produced the most impressive results, with less than 80 percent canopy scorch while adjacent untreated areas were nearly completely consumed. The Fischer fire was the only site where fire severity was not significantly reduced by this type of treatment. However, fire severity in untreated plots at this site was among the lowest we sampled, suggesting that the Fischer treatments may not have received an adequate test of their potential effectiveness. This supposition is further supported by the relatively moderate weather conditions when the Fischer treatments were affected by wildfire (Table 2).

Differences between treated and untreated areas in soil heating, as indicated by ground char ratings, were less evident. The average ground char rating in treated plots was 1.73, versus 1.78 in untreated plots. Among treatment types, ground char was lowest in areas that received surface treatments and highest in areas that were thinned without slash treatment (Table 5). The only treatments that significantly reduced ground char at an individual site were the prescribed burn areas of the Aspen fire. While ground char was not a generally informative indicator of treatment effectiveness, it was an important predictor of non-native plant establishment (see section 3.4 below).

Table 3. Comparison of reconstructed stand conditions between treated and untreated areas within the five sampled wildfires.(means with standard deviations in parentheses).

Site / Treatment	Stand Density (Trees/ha)	Canopy Bulk Density (kg/m³)	Effective Canopy Base Height (m)	Tree Diameter (cm)
Hayman / Surface				
Treated (n=6)	719 (491)	0.08 (0.07)	2.3 (0.7)	20.0 (9.5)
Untreated (n=6)	758 (535)	0.06 (0.02)	2.5 (1.6)	20.8 (11.8)
Difference (U-T)	39	-0.02	0.2	0.8
Hayman / Canopy				
Treated (n=5)	255 (241)	0.04 (0.02)	3.1 (1.1)	29.0 (11.1)
Untreated (n=5)	250 (158)	0.05 (0.03)	3.6 (3.6)	26.2 (5.8)
Difference (U-T)	-5	0.01	0.5	-2.8
Hayman / Combination				
Treated (n=8)	571 (502)	0.06 (0.05)	4.6 (3.8)	27.0 (5.9)
Untreated (n=8)	536 (596)	0.07 (0.04)	3.1 (1.7)	28.2 (13.0)
Difference (U-T)	-35	0.01	-1.5	1.2
Aspen / Surface				
Treated (n=9)	1,136 (765)	0.11 (0.05)	4.6 (2.6)	23.5 (8.3)
Untreated (n=9)	1,424 (997)	0.12 (0.04)	3.3 (2.0)	24.1 (12.2)
Difference (U-T)	288	0.01	-1.3	0.6
Aspen / Canopy				
Treated (n=8)	685 (349)	0.12 (0.06)	4.4 (1.2)	30.6 (7.4)
Untreated (n=8)	777 (56.5)	0.08 (0.03)	3.7 (2.1)	31.5 (6.7)
Difference (U-T)	92	-0.04	-0.7	0.9
Davis/Canopy				
Treated (n=21)	514 (792)	0.08 (0.07)	8.8 (5.5)	41.0 (16.0)
Untreated (n=21)	1,682 (1,000)	0.15 (0.09)	4.2 (3.6)	22.8 (11.5)
Difference (U-T)	**1168[d]**	**0.07[c]**	**-4.6[d]**	**-18.2[d]**
Davis / Combination				
Treated (n=4)	399 (278)	0.07 (0.03)	9.1 (4.0)	38.6 (16.1)
Untreated (n=4)	1,192 (427)	0.06 (0.02)	5.9 (2.7)	30.3 (16.1)
Difference (U-T)	**793[b]**	-0.01	-3.2	-8.3
Fischer / Combination				
Treated (n=11)	126 (99)	0.03 (0.01)	9.6 (5.7)	41.0 (8.4)
Untreated (n=11)	862 (754)	0.10 (0.09)	4.2 (3.1)	31.5 (14.5)
Difference (U-T)	**736[c]**	**0.07[b]**	**-5.4[c]**	**-9.5[a]**
Power / Surface				
Treated (n=9)	192 (128)	0.04 (0.01)	17.0 (10.3)	63.3 (17.8)
Untreated (n=9)	1,138 (1,175)	0.10 (0.10)	5.4 (8.4)	41.0 (27.1)
Difference (U-T)	**946[b]**	**0.06[a]**	**-11.6[b]**	**-22.3[c]**
Power / Canopy				
Treated (n=9)	249 (248)	0.04 (0.02)	10.8 (5.8)	53.4 (18.0)
Untreated (n=9)	1,223 (1,406)	0.13 (0.09)	4.9 (8.1)	33.8 (16.0)
Difference (U-T)	**974[b]**	**0.09[b]**	**-5.9[a]**	**-19.6[b]**

Notes:

An emboldened value indicates a significant difference between the treated mean and corresponding untreated mean in the hypothesized direction at the significance level indicated by the superscript:

[a] $p<0.1$.

[b] $p<0.05$.

[c] $p<0.01$.

[d] $p<0.001$.

Table 4. Comparison of fire severity as indicated by percent crown volume scorched plus percent consumed (S+C) between treated and untreated areas within the five sampled wildfires (means with standard deviations in parentheses).

Treatment Type/Age	Hayman	Aspen	Davis	Fischer	Power
Surface < 10 yr					
Treated S+C (%)	20 (16)	28 (30)			26 (34)
Untreated S+C (%)	84 (35)	85 (75)			85 (30)
N (# pairs)	3	9			5
p-value	**0.082**	**0.043**			**0.047**
Canopy < 2 yr					
Treated S+C (%)	162 (45)		121 (41)		6 (8)
Untreated S+C (%)	144 (69)		171 (40)		61 (48)
N (# pairs)	5		9		4
p-value	0.419		**0.003**		0.109
Combination < 2 yr					
Treated S+C (%)	48 (45)		77 (48)	44 (37)	
Untreated S+C (%)	173 (35)		182 (35)	64 (49)	
N (# pairs)	3		4	11	
p-value	**0.043**		**0.091**	0.598	
Surface >10 yr					
Treated S+C (%)	197 (2)				98 (7)
Untreated S+C (%)	198 (2)				96 (59)
N (# pairs)	3				4
p-value	0.133				0.866
Canopy > 2 yr					
Treated S+C (%)		98 (71)	109 (61)		49 (37)
Untreated S+C (%)		79 (56)	145 (67)		89 (17)
N (# pairs)		8	12		5
p-value		0.490	0.134		**0.058**
Combination > 9 yr					
Treated S+C (%)	122 (75)				
Untreated S+C (%)	129 (86)				
N (# pairs)	5				
p-value	0.913				

Notes:

Emboldened p-values indicate a significant difference in fire severity between treated and untreated areas. All p-values indicate the significance level for two-tailed tests, i.e. the direction of effect was not specified *a priori.*

Table 5. Comparison of fire severity as indicated by ground char ratings between treated and untreated areas by the three broad treatment types represented across the five sampled wildfires (means with standard deviations in parentheses).

| | Treatment Type | | |
	Surface	Canopy	Combination
Treated Ground Char Rating (0-3)	1.56 (0.36)	1.86 (0.36)	1.64 (0.30)
Untreated Ground Char Rating (0-3)	1.73 (0.29)	1.86 (0.36)	1.68 (0.40)
N (# pairs)	24	43	23
p-value	**0.075**	0.972	0.660

Notes:
Emboldened p-values indicate a significant difference in fire severity between treated and untreated areas. All p-values indicate the significance level for two-tailed tests, i.e. the direction of effect was not specified *a prioiri.*

Simulation studies have suggested that effective treatments can provide a value-added benefit in protecting untreated areas immediately behind them (Loehle 2004; Finney 2001). We found few opportunities to test this hypothesis empirically due to confounding influences behind most of the treatment areas we sampled, such as the edge of the wildfire, additional treatments, or a change in topography or burning day. However, the Power and Davis fires did offer a few opportunities (Figures 4 and 6).

Canopy scorch/consumption in the Power and Davis fires averaged 124 percent behind treatments that effectively reduced fire severity, somewhat less than the 134 percent canopy scorch/consumption in adjacent unprotected areas. This effect was not found to be significant (n=8, two-tailed p=0.563). On the other hand, canopy scorch/consumption was significantly greater behind ineffective treatments (those where fire severity was greater than in adjacent untreated comparison plots), than in adjacent 'unprotected' areas (155% vs. 58% in 'protected' and 'unprotected' areas, respectively; n=3, two-tailed p=0.034). Though based on a very limited sample, this result supports the hypothesis that fuel treatment activities have consequences for fire behavior beyond their perimeters. However, the magnitude of these effects is likely dependent on the size and arrangement of the treated units relative to the area burned by wildfire, variables that may be better analyzed in a simulation environment (e.g., Finney 2001).

3.3 Correlations between Stand Conditions and Wildfire Severity
The most effective fuel treatments should be those that effectively reduce crown fire hazard or increase fire resistance by decreasing stand density and canopy bulk density or increasing the height to canopy and mean tree diameter. But correlations between fuel treatment effects on wildfire severity and altered stand conditions varied by treatment type.

Somewhat surprisingly, the strongest correlations between treatment effectiveness and stand conditions were among surface treatments (Table 6). We found recent prescribed burns to be the most consistently effective fuel treatments (Table 4) even though most did not significantly alter the stand condition variables that we were able to reconstruct post-

fire (Table 3). Nonetheless, correlation analysis suggests that the most effective surface treatments not only reduce surface litter, but also serve as a low thinning that removes small diameter trees, effectively increasing mean tree diameter and height to canopy and reducing canopy bulk density.

Table 6. Correlations between paired plot differences (untreated minus treated) in fire severity and differences in stand condition, as well as age of treatment and weather conditions when sampled plots burned. Correlations are separated by the three broad treatment types represented across the five sampled wildfires.

	Fire Severity (% Crown Volume Scorch + Consumption)		
	Surface Treatments (n = 24 pairs)	Canopy Treatments (n = 43 pairs)	Combination Treatments (n = 23 pairs)
Stand Density (trees/ha)	0.26	0.15	0.13
Canopy Bulk Density (kg/m3)	0.46 [b]	0.08	-0.11
Effective Canopy Base Height (m)	-0.36 [a]	-0.20	-0.40 [a]
Mean Tree Diameter (cm)	-0.51 [b]	-0.11	-0.26
Treatment Age (yr)	-0.14	-0.44 [c]	-0.29
Weather Conditions (Burning Index percentile)	0.08	-0.16	0.38 [a]

Notes:
Emboldened correlation coefficients are different from zero at the two-tailed significance level indicated by the superscript:
[a] $p < 0.1$.
[b] $p < 0.05$.
[c] $p < 0.01$.

In contrast, the effectiveness of thin-only treatments was not significantly correlated to any of the stand condition variables we measured (Table 6), even though thin-only treatments were generally the most effective in altering these variables (Table 3). Instead, the effectiveness of thin-only treatments was significantly correlated only with the age of the treatment. Only very recent (less than one year old) treatments of this type were found to be effective, most likely due to the slash still being green when encountered by wildfire.

The effectiveness of combination treatments was significantly correlated to their increased canopy base heights. But the effectiveness of these treatments was probably most influenced by how completely the activity fuels were removed by subsequent surface treatment, a variable we were not able to reliably assess. These treatments were the only ones that showed a significant correlation to weather severity, as indicated by the Burning Index of the National Fire Danger Rating System (Deeming et al. 1977). Somewhat surprisingly, the effectiveness of combination treatments increased with

weather severity. How well this relationship holds under the increasingly extreme weather conditions predicted by climate change scenarios (e.g., Flannigan et al. 2000) remains to be seen.

3.4   Non-native Plants

Native and non-native species richness and cover varied significantly between sites following fire. Mean native species richness per plot ranged from a maximum of 42 species at the Hayman site to 6 species per plot at the Aspen site. Mean native species cover ranged from 42% at the Fischer site to only 4% cover at the Aspen site. Non-native species richness reached its maximum at the Hayman site (4 species per plot) compared to the Davis site where no non-native species were found on plots. Non-native species cover reached its maximum at the Fischer site (2% cover) while the Davis site had 0% cover of non-native species (Table 7).

Table 7. Plant species richness and percent cover at each of the sampled five wildfires (means with standard errors in parentheses).

Site	Native richness (# species)	Non-native richness (# species)	Native cover (%)	Non-native cover (%)
Hayman	42 (1)	4 (0)	8 (1)	1 (0)
Aspen	6 (1)	< 1 (0)	4 (1)	1 (0)
Davis	8 (0)	0	7 (2)	0
Fischer	17 (1)	2 (0)	42 (5)	2 (1)
Power	8 (1)	1 (0)	8 (2)	< 1 (0)

Wildfire was associated with significant increases in non-native richness and cover and significant decreases in native cover across sites. These effects were magnified in high severity plots, though not significantly so. Native richness was significantly higher in low severity plots than it was in either unburned plots or high severity plots (Figure 7). No significant effects where found between different types of fuel treatment (prescribed fire versus non-fire mechanical treatments). But when fuel treatments were grouped, a significant increase was found in native richness (p=0.008) and non-native richness (p<0.0001) and cover (p<0.0001) when a site by treatment interaction effect was included in the Analysis of Variance. More research is necessary to determine exactly what fuel treatment characteristics lead to invasion by non-native species and how non-native species composition and cover changes over time, since we only sampled one or two seasons post-fire. Other possible influences that remain to be investigated include precipitation, soil micronutrients, site productivity, and distance to seed source, roads, trails, and fire perimeter.

But our results show that wildfire consistently led to a significant reduction in native cover and an increase in non-native richness and cover. Wildfire significantly and directly altered several important environmental variables. Stand damage (r = -0.58, p < 0.0001) and ground char (r = -0.44, p < 0.0001) both significantly reduced canopy cover and increased the percentage of bare ground (r = 0.60, p < 0.0001 and r = 0.51, p < 0.0001 respectively: Table 8). Bare soil exhibited a significant positive correlation with

native and non-native richness and a significant negative correlation with native cover. A non-significant, positive correlation existed between bare soil and non-native cover. Additional, long-term monitoring will be required to determine whether non-native species pose a significant, long-term threat to these post-fire and post-fuel treatment stands.
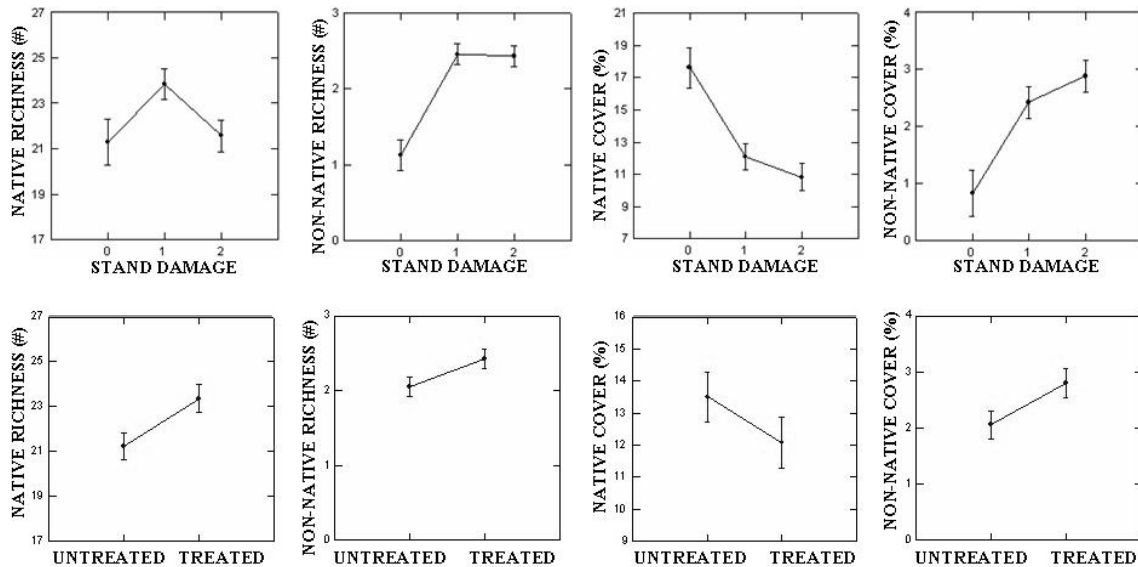

Figure 7. Effects of wildfire (0=no canopy scorch, 1=some canopy scorch, 2=complete canopy scorch) and fuel treatments on native and non-native richness and cover. Analysis of Variance model includes site and site*burning or site and site*treatment effects.

Table 8. Significant (p<0.05) correlations among biotic and abiotic variables across all sites.

	Native cover (%)	Non-native cover (%)	Native richness (# species)	Non-native richness (# species)
Treated				
Burned	-0.17	0.16		0.28
Canopy Damage (0-4)	-0.21	0.11		0.20
Ground char (0-3)	-0.25		-0.23	
Canopy cover (%)	0.10			
Bare soil (%)	-0.24		0.13	0.19
PDIR [a]	-0.10	-0.42	-0.44	-0.34
Soil C (%)		-0.12	-0.16	-0.12
Soil N (%)				
Soil Clay (%)	0.13		0.18	0.13
Elevation (m)	-0.37	0.25	0.51	0.42

Notes:
[a] Potential direct incident radiation (PDIR) is a function of aspect, slope, and latitude. Transformations followed Beers et al. (1966) and McCune and Keon (2002).

4   Conclusions

A wildfire encounters numerous fuel profiles as it spreads over a landscape. Spatial and temporal changes in the amount, size, moisture, chemistry, and depth of fuelbed in various strata (i.e., ground, surface, and aerial fuels) provide innumerable possibilities for the type of fire behavior that may be observed at a particular place. Further, our analyses were conducted along a broad geographical gradient for mixed conifer forests in the western US. Historical fire incidence for our study sites most likely varied, from frequent low severity regimes in California to less-frequent mixed-severity regimes in Colorado. Thus, our results may reflect regional differences in forest structure as well as unmeasured interactions among climate, land use, and elevation. Inferences beyond our study sites should therefore be made with caution.

Our results indicate that fuel treatments such as prescribed burning and/or mechanical thinning may alter fuel properties to reduce fire hazards. Treatment of surface fuels appears to be of primary importance for reducing the intensity and severity of subsequent wildfire. Surface treatments such as prescribed burns may be effective for as long as 10 years, especially if they raise the height to canopy and increase mean tree diameter. However, in many areas prescribed fire may no longer be feasible without substantial preliminary thinning. The most effective treatments sampled in this study did include mechanical thinning, but it is critical that the resultant slash from such activities be treated within a year or two. Without slash treatment, mechanical thinning may increase potential wildfire severity. Whether management activities increase or decrease fuel hazards, the consequences for fire intensity and severity are likely to be contagious beyond the perimeter of the treatment units should they become involved in a wildfire.

Fuel treatments that slow or reduce the flaming intensity of an oncoming flaming front can buffer a community or valued resource. In other instances a treatment may increase management options, such as facilitating wildfire suppression by providing safe access and egress for firefighters, as well as possible counter-firing opportunities. Fuel treatments may also help restore fire to its historic regime, either by restoring fuel profiles that facilitate safe management ignitions or by buffering the border between values-at-risk and extensively managed areas where natural ignitions are allowed to play themselves out.

Regardless of their objectives, however, fuel treatments that reduce canopy cover and increase soil exposure can facilitate establishment of non-native plants. But our results suggest that the role of fuel treatments in promoting non-native species is less important than that of wildfire. Fire severity appears to play the primary role in predicting plant species composition in the first post-fire year in the forest systems sampled in this study. Low severity fire can increase native species richness, while high severity fires, through the opening of the forest canopy and increasing bare ground, create conditions most ideal for the growth of opportunistic non-native plant species.

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Appendix: Dissemination

A.1 Manuscripts

Freeman, J.P. 2006. Rapid Response to Post-fire Plant Invasion. M.S Thesis. Colorado State University, Fort Collins.

Freeman, J.P., T.J. Stohlgren, M.E. Hunter, P.N. Omi, E.J. Martinson, G.W. Chong, and C.S. Brown. *In Press*. Rapid Assessment to Post-Fire Plant Invasions. Ecological Applications.

Martinson, E.J. and P.N. Omi. 2006. Assessing mitigation of wildfire severity by fuel treatments - an example from the Coastal Plain of Mississippi. USDA Forest Service Proceedings RMRS-P-41:429-439. (http://www.fs.fed.us/rm/pubs/rmrs_p041.html).

Martinson, E.J., M.E. Hunter, J.P. Freeman, and P.N. Omi. *In press*. Effects of fuel and vegetation management activities on non-native invasive plants. Chapter 13 in Wildland Fire in Ecosystems: Fire and Nonnative Invasive Plants. USDA Forest Service General Technical Report RMRS-GTR-42-vol. 6.

Martinson, E.J. and P.N. Omi. *In press*. Assessing mitigation of wildfire severity by fuel treatments - an example from the Coastal Plain of Mississippi. International Journal of Wildland Fire.

A.2 Presentations

3rd International Fire Ecology and Management Congress, November 2006, San Diego, CA: Special Session on Fire and Non-native Invasive Plants.

3rd International Fire Ecology and Management Congress, November 2006, San Diego, CA: "*Initial response of non-native plant species after wildfire in three conifer forests of the Pacific Northwest*".

1st Fire Behavior and Fuels Conference, March 2006, Portland, OR: "*Assessing mitigation of wildfire severity by fuel treatments*".

Southern Interior Silvicultural Committee Meeting, March 2005, Penticton, BC: "*Effects of fuel treatment on wildfire severity*".

Ecological Society of America Annual Meeting, August 2004, Portland, Oregon: "*Effects of pre-fire fuel reduction treatments on post-wildfire non-native plant species richness and cover*"

Ecological Society of America Annual Meeting, August 2004, Portland, Oregon: "*Coarse woody debris and fuel treatments—implications for salvage*"

International Association of Vegetation Science Annual Meeting, July 2004, Kailua-Kona, HI: "*Retrospective analysis of fuel treatment performance under extreme wildfire conditions*".

2nd International Fire Ecology and Management Congress, November 2003, Orlando, FL: "*Fuels, fires, invasions, and some effects of active management in the eastern Rockies*".

USFS National Program for Fire Systems Research meeting, August 2003, Fort Collins, CO: "*Retrospective sampling of fuel treatment effectiveness - some pitfalls and suggestions*".